Bin Updates and Uncertainties for VBF and VH

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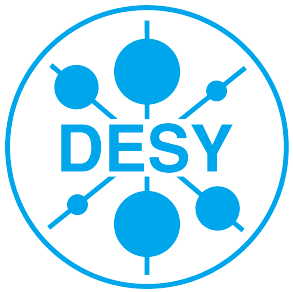
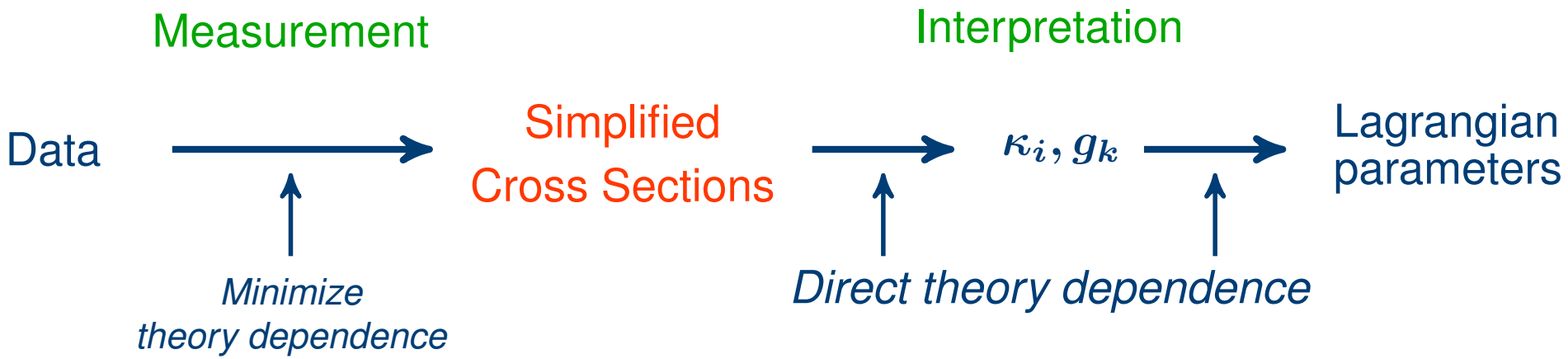
Based on recent discussions at Les Houches
and in fidSTXS subgroup



Reminder.

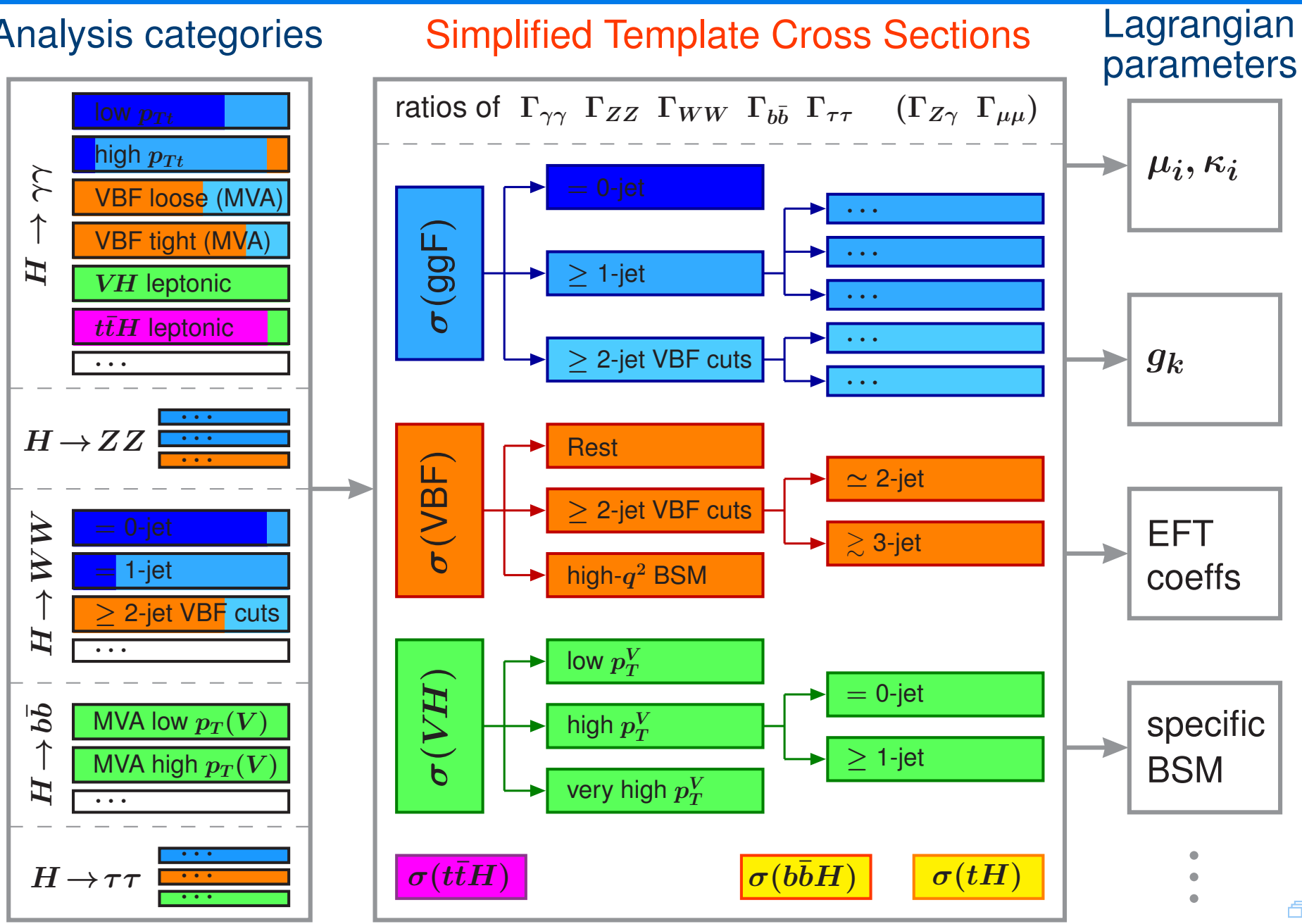
Separating Measurement from Interpretation.



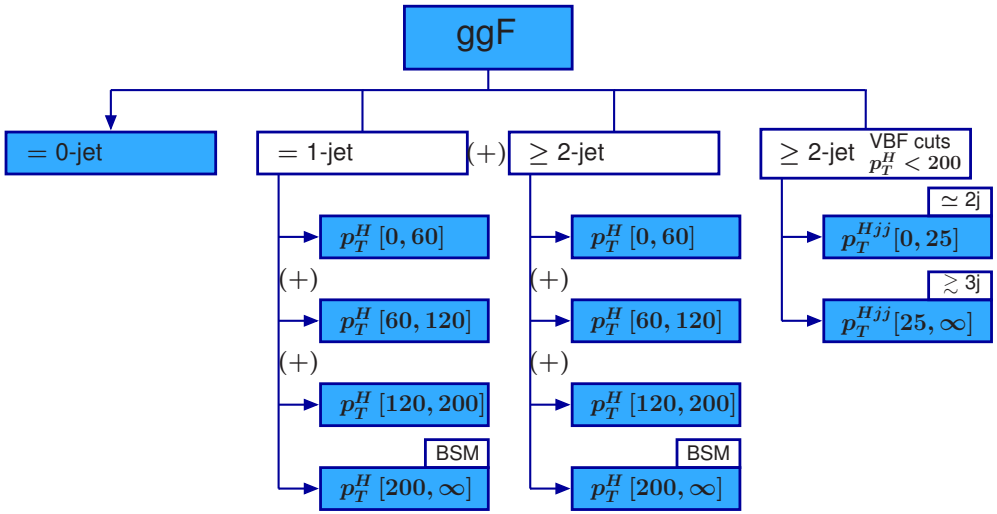
Goals

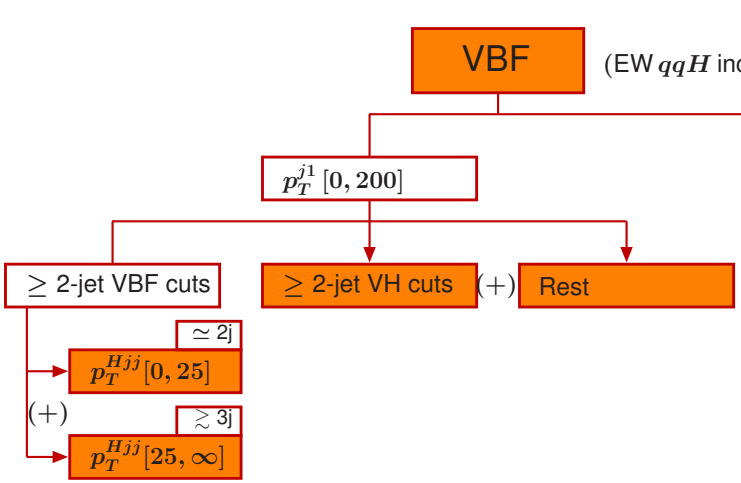
- Minimize dependence on theory systematics in measurements
  - Clearer and systematically improvable treatment at interpretation level (acceptance corrections, extrapolations to total xsec, ...)
- Minimize model dependence in measurements
  - Decouples measurements from discussions about specific models (SM, linear/nonlinear EFT, BSM models, ...)
- Measurements stay long-term useful
- Allows easy (re)interpretation with different theory inputs/assumptions
  - Improved theory predictions/uncertainties
  - μ_i, κ_i, anomalous couplings, EFT coefficients, specific BSM scenarios

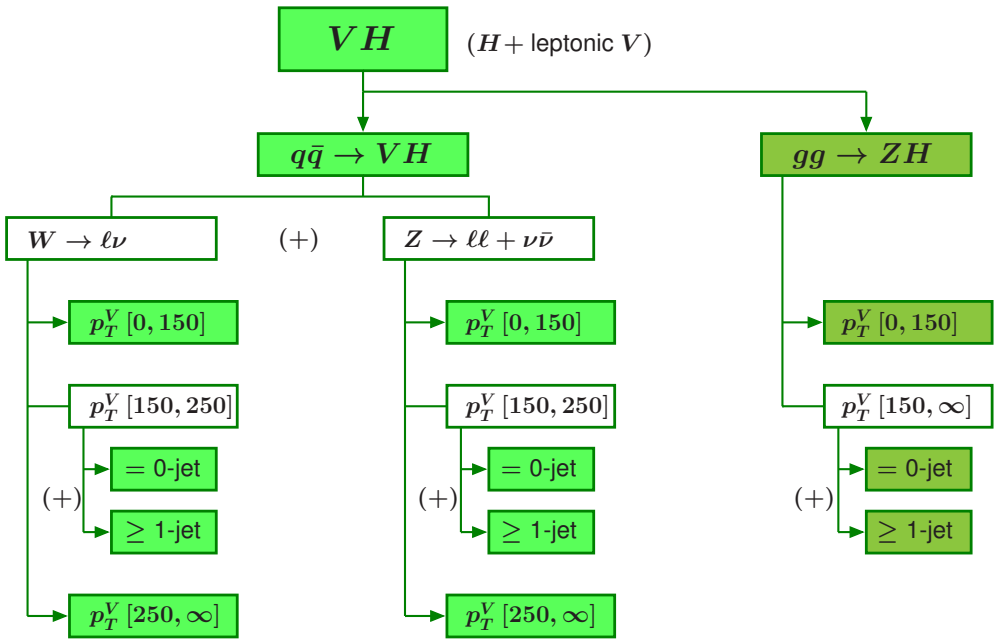
Simplified Template Cross Section Framework.



Stage 1 Bins.


ggF
= 0-jet
= 1-jet
(+)
≥ 2-jet
≥ 2-jet VBF cuts $p_T^H < 200$
p_T^H [0, 60]
p_T^H [60, 120]
p_T^H [120, 200]
BSM
p_T^H [200, ∞]
≃ 2j
p_T^{Hjj} [0, 25]
≳ 3j
p_T^{Hjj} [25, ∞]


VBF
(EW qqH incl. $VH \to qqH$)
p_T^{j1} [0, 200]
BSM
p_T^{j1} [200, ∞]
≥ 2-jet VBF cuts
≥ 2-jet VH cuts
(+)
Rest
≃ 2j
p_T^{Hjj} [0, 25]
(+)
≳ 3j
p_T^{Hjj} [25, ∞]


VH
(H + leptonic V)
$q\bar{q} \to VH$
$gg \to ZH$
$W \to \ell\nu$
(+)
$Z \to \ell\ell + \nu\bar{\nu}$
p_T^V [0, 150]
p_T^V [150, 250]
= 0-jet
≥ 1-jet
p_T^V [250, ∞]
p_T^V [150, ∞]

Binning Updates.

Staging and Bin Merging.

Defined different stages for each production mode

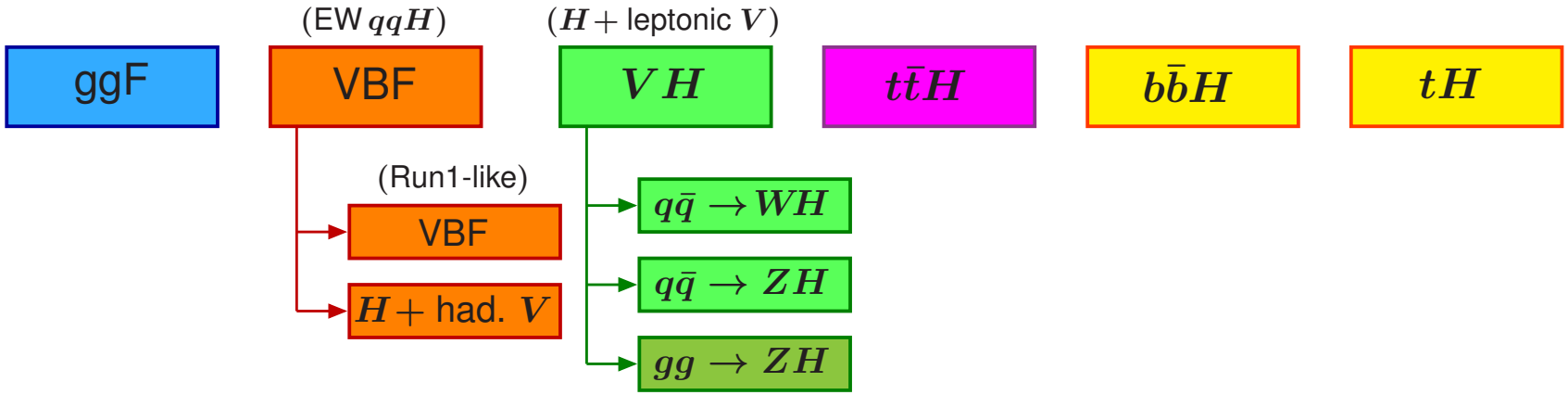
- Stage 0: Closest correspondence to Run 1
- Stage 1: “Minimal” hoped-for splitting for Run 2
- Stage 2: To be defined ...

Evolution and merging of bins

- Individual channels can quote sum of bins where there is no sensitivity
  - Possible bin merging is indicated by “$(+)$”
  - Avoid merging bins across production channels (e.g. ggF+VBF)
- More information is better, so try to minimize merging
  - Even limits in high-p_T bins are very useful/interesting
  - Do not merge bins “just” because they are correlated
  - Each merging can move a possibly nontrivial theory uncertainty from interpretation back into measurement

$\Rightarrow$ If necessary, consider providing two sets of results with different levels of merging

Hadronic VH.



Template processes are defined for a stable Higgs but decayed V

- "VH" is defined as $pp \to V(\to \text{leptons})H$, split into
  - $q\bar{q} \to W(\to \ell\nu)H$, $q\bar{q} \to Z(\to \ell\bar{\ell}, \nu\bar{\nu})H$, $gg \to Z(\to \ell\bar{\ell}, \nu\bar{\nu})H$
- $q\bar{q} \to V(\to qq)H$ is part of "VBF" (EW qqH production)
  - Targeted via dedicated "VBF" bin with $V(\to jj)H$ topology cuts
  - Higher-order "VBF" calculations already include hadronic VH "background"
- $gg \to Z(\to q\bar{q})H$ is part of "ggF"
  - Effectively considered a (real-emission) EW correction to ggF
  - Currently no experimental sensitivity, swamped by ggF+2jets
  - In the future could split out of ggF bin with $V(\to jj)H$ topology cuts
  - Also theoretically it makes the most sense to treat it like this

ggF, $b\bar{b}H$, $t\bar{t}H$.

ggF

- Consider to split the highest p_T^H bins into [200, 500] and [500, ∞] to have a dedicated bin for boosted $H \to b\bar{b}$ analyses
  - First CMS results show feasibility
  - Sensitivity starts above around 500
- Also possibly split at $2m_t$ into [200, 350] and [350, 500]
  - in sync with fiducial measurements
- These high-p_T^H bins are not split further into $=$1j and $\geq$2j bins

$b\bar{b}H$

- Current Stage 1 has one inclusive bin for $b\bar{b}H$
- Consider absorbing this into ggF
  - Currently no experimental sensitivity/distinction from ggF (would require dedicated reco categories with low-p_T b-tag)
  - Do not want to assume/inject SM prediction for $b\bar{b}H$ in measurement

$t\bar{t}H$

- Current Stage 1 has one inclusive bin for $t\bar{t}H$
  - Include also tH in this
- Consider split by p_T^H: [0,200] and [200, ∞]
  - To separately target nonboosted and boosted analyses, precise cut value to be discussed
- Have also been thinking about splitting of [0, 200] bin into $=$0j and $\geq$1j (in addition to $t\bar{t}H$ signal jets)
  - still unclear if actually useful/needed

Theory Uncertainties for VBF and VH.

Theory Uncertainties.

Two aspects to theory uncertainties

- Residual theoretical uncertainties related to “unfolding” experimental event categories to STXS bins
- Uncertainties in interpretation of STXS bins, i.e. in SM (or beyond) cross section predictions for each bin
  - Also enter as “residual” uncertainties in measurement whenever bins with different sensitivities are merged

Implementation of uncertainties (in measurement or interpretation)

- Requires uncertainties per bin and their correlations
  - Particularly important when binning cut itself introduces a source of uncertainty that affects each bin but cancels in their sum
  - Implementation in terms of $\pm 100\%$ correlated or uncorrelated nuisance parameters

$\rightarrow$ Need to identify and distinguish different sources of uncertainties and evaluate also their correlations between kinematic bins

- Use generic parametrization of uncertainties in kinematic bins as discussed in YR4 Section 1.4.2a

Uncertainties With Multiple Bin Boundaries.

- Each bin can have multiple boundaries, and each boundary can be shared by different bins
- Consider given bin boundary when all additional subdivisions are removed and parametrize in terms of independent yield and migration uncertainties
- Consider binning cut "a/b" with $\sigma_{ab} = \sigma_a + \sigma_b$ and associated $\Delta_{a/b}$ (anticorrelated between σ_a and σ_b)
  - Allow for additional subbins such that $\sigma_a = \sum_i \sigma_a^i$ and $\sigma_b = \sum_j \sigma_b^j$
  - Consider binning uncertainty as fully correlated among subbins and implement with a single nuisance parameter

$$\theta_{a/b}: \quad \Delta_{a/b} \times \{\{x_a^i\}, -\{x_b^j\}\} \qquad \text{with} \qquad \sum_i x_a^i = \sum_j x_b^j = 1$$

  where x_a^i and x_b^j specify how $\Delta_{a/b}$ gets distributed among the subbins
- Consider each binning cut/bin boundary as potential uncertainty source
  - Migration uncertainty between σ_a and σ_b, and yield uncertainty inside each
  - Limiting case: Global yield uncertainty for total xsec

Parametrization of VH Uncertainties: Sources.

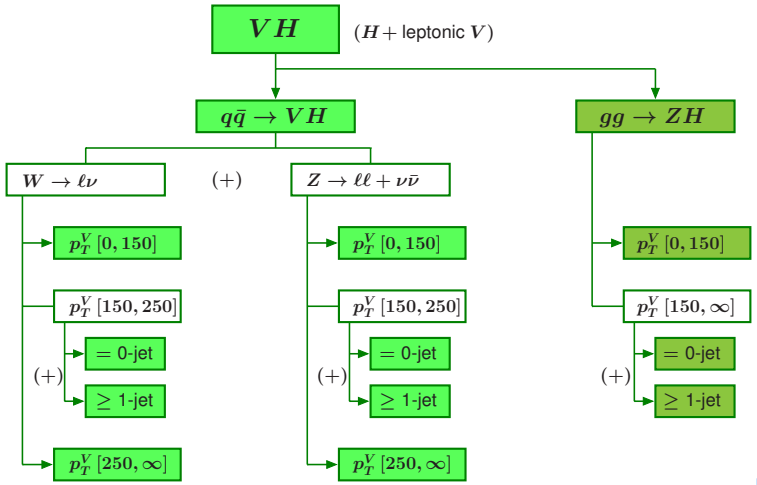
QCD uncertainties

- Δ_μ, Δ_{150}, Δ_{250}
  - Option 1: overall yield uncertainty plus two p_T^V binning (shape) uncertainties
  - Option 2: one uncorrelated uncertainty for each p_T^V bin
- $\Delta_{0/1}$: jet bin migration uncertainty
- Same nuisance parameter for W and Z (i.e. 100% correlated)

EW uncertainties

- Δ_{Sud}: EW Sudakov effects (correlated between W and Z)
- Δ_W, Δ_Z, Δ_γ
  - Separate uncertainties for non-Sudakov contributions

- Separate sources (uncorrelated uncertainties) for $q\bar{q} \to VH$ and $gg \to ZH$
  - Study which sources for $gg \to ZH$ should be correlated with $gg \to H$
- Some of this also impact "VBF" bins through its hadronic VH contribution



Parametrization of VH Uncertainties.

Bin	QCD uncertainties (Option 1)				EW uncertainties			
	Δ_μ	Δ_{150}	Δ_{250}	$\Delta_{0/1}$	Δ_{Sud}	Δ_W	Δ_Z	Δ_γ
W [0,150]	x_1	$-c$	0		y_1	$*$		$*$
W [150,250]	x_2	$+c$	$+d$	0	y_2	$*$		$*$
$=$0j [150,250]	$x_2 z$	$+cz$	$+dz$	$+1$	$\cdots$	$*$		$*$
$\geq$1j [150,250]	$x_2(1-z)$	$+c(1-z)$	$+d(1-z)$	-1	$\cdots$	$*$		$*$
W [250,∞]	x_3	0	$-d$		y_3	$*$		$*$
Z [0,150]	x_1	$-c$	0		y_1		$*$	
Z [150,250]	x_2	$+c$	$+d$	0	y_2		$*$	
$=$0j [150,250]	$x_2 z$	$+cz$	$+dz$	$+1$	$\cdots$		$*$	
$\geq$1j [150,250]	$x_2(1-z)$	$+c(1-z)$	$+d(1-z)$	-1	$\cdots$		$*$	
Z [250,∞]	x_3	0	$-d$		y_3		$*$	

$+$ Analogous uncorrelated sources for $gg \to ZH$

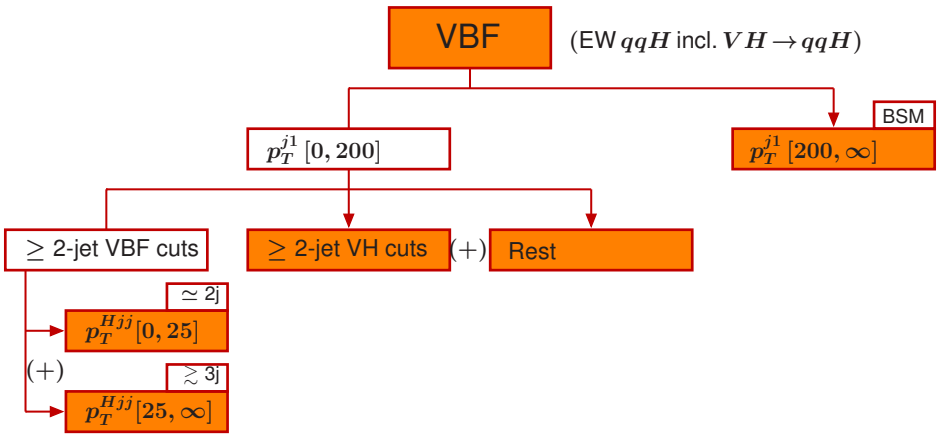
Parametrization of VBF uncertainties: Sources.

QCD uncertainties

- Q: How are unc. in different m_{jj} regions correlated?
  - Option 1: single overall yield Δ_{μ} plus m_{jj} shape/migration Δ_{mjj}
  - Option 2: uncorrelated sources Δ_{low} and Δ_{high} for low and high m_{jj}
  - Option 3: ???
- Δ_{μ}^{VH} uncertainty for the VH bin induced by hadronic VH process
  - Correlated with leptonic VH
- Δ_{200} migration uncertainty related to p_T^{j1} cut
- Δ_{25} migration uncertainty related to 2/3-jet separation

EW uncertainties

- Δ_{Sud}: EW Sudakov effects
  - correlated with $q\bar{q} \to VH$ (?)
- Δ_{hard}
  - uncorrelated with $q\bar{q} \to VH$ (?)



Parametrization of VBF uncertainties.

Bin	QCD uncertainties (Option 2)					EW uncertainties		
	Δ_{low}	Δ_{high}	Δ_{μ}^{VH}	Δ_{200}	Δ_{25}	Δ_{Sud}	Δ_{hard}	$\Delta_{W,Z,\gamma}^{\text{VH}}$
p_T^j [0,200]	≈ 1	≈ 1	≈ 1	-1		y_1	$*$	
VBF cuts	≈ 0	≈ 1	≈ 0	$-x_1$	0	y_2	$*$	
p_T^{Hjj} $[0, 25]$		z		$-x_1 z$	$+1$	$\cdots$	$*$	
p_T^{Hjj} $[25, \infty]$		$1-z$		$-x_1(1-z)$	-1	$\cdots$	$*$	
VH cuts	?	?	≈ 1	$-x_2$		y_3	$*$	1
Rest	≈ 1	≈ 0	?	$-x_3$		y_4	$*$	
p_T^j $[200, \infty]$	?	?	?	$+1$		$1-y_i$	$*$	

Discussion.

We need a consistent/common/coherent treatment of theory uncertainties across kinematic regions and across production modes

- One goal is for interpretation to be able to easily switch between different predictions
  - This is why we focus first on generic parametrization given the bins we have
  - Discussing with VH and VBF subgroups
- Same approach as already followed for ggF bins
- This is a first “not-so-minimal” proposal, which we think could work
- We are asking for feedback, in particular
  - Any objections?
  - Anything missing?
  - Is this sufficiently general for the EW corrections (at least as a first step)?

Backup Slides

Defining Features.

- Measure cross sections but separated into production modes
  - Allows different efficiencies/acceptances for different production modes without incurring dependence on SM production mode mix
  - SM processes act as kinematic templates
  - Future: Can add more kinematic templates (e.g. CP-odd Higgs)
- Non-Higgs backgrounds are subtracted
  - Future: Can add templates for BSM sensitive backgrounds (e.g. $pp \to WW$)
- Inclusive over the Higgs decays
  - Can perform a global combination of channels
- "Simplified" bin definitions abstracted from the actual measurement categories
  - Allow some acceptance corrections,
  - Analyses can use optimized selections at reconstruction level, MVAs ...
  - Avoid extrapolations that are unnecessary or nontrivial (i.e. theory sensitive)

$\Rightarrow$ Maximize sensitivity while reducing theory dependence

Fiducial vs. Simplified Template Cross Sections.

Fiducial: Optimized for maximal theory independence

- Minimize acceptance corrections
- Simple (rectangular) signal cuts
- “Exact” fiducial volume
- Fiducial in Higgs decay
- Targeted object definitions

Simplified: Maximize sensitivity while reducing theory dependence

- Allow larger acceptance corrections
- Allow event categories, MVAs, ...
- Abstracted/simplified fiducial volumes
- Inclusive in Higgs decay
- Common idealized object definitions

Agnostic to production modes

(Single-)differential distributions
(overlapping events)

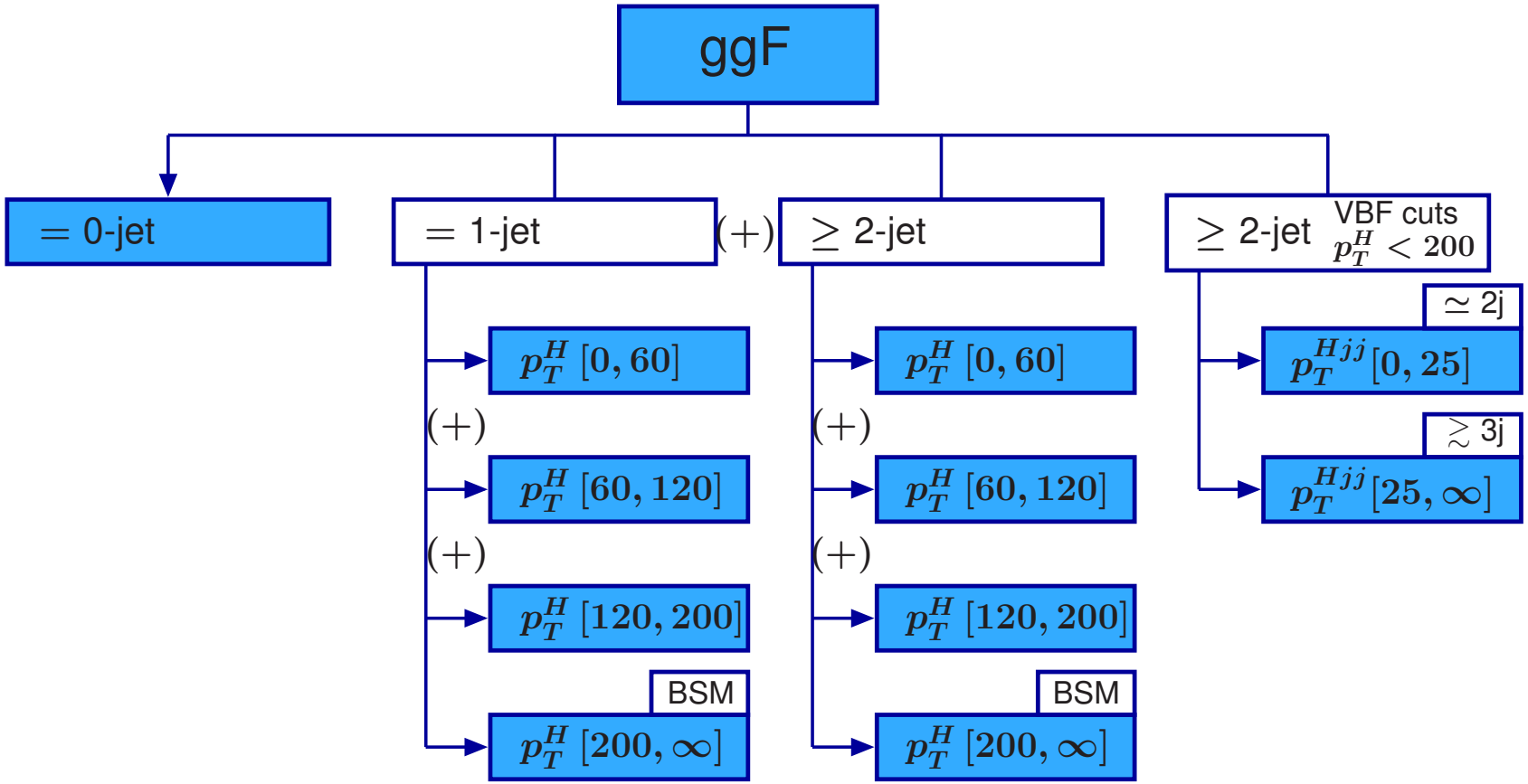
Only $H \to \gamma\gamma, ZZ, (WW)$
(by default no combination of channels)

Xsec split by production mode

Xsec split into mutually exclusive regions of phase space

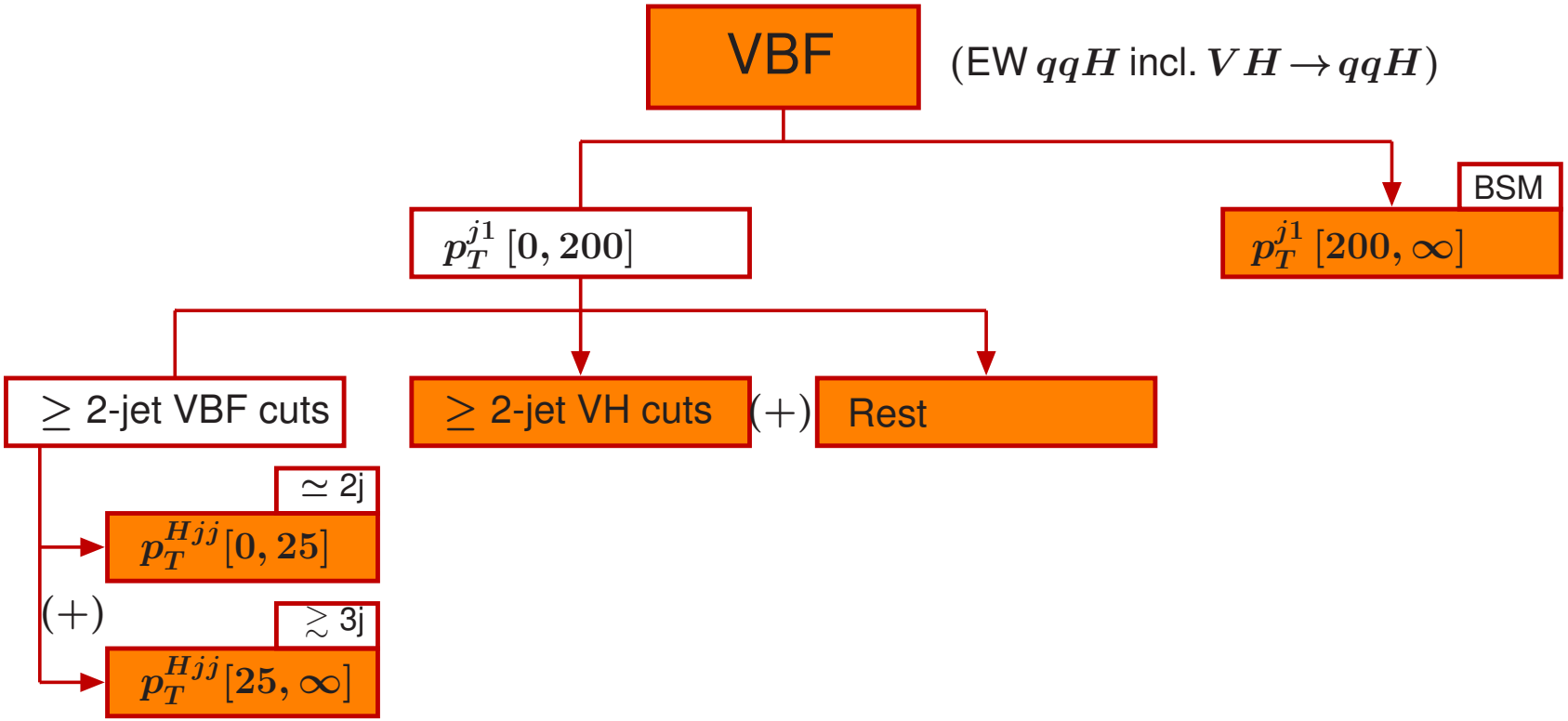
Explicitly designed for combination of all decay channels

Gluon Fusion – Stage 1.



- Jet bins motivated by experimental analyses
- High p_T^H bins target boosted categories ($\tau\tau$) and BSM overflow
- VBF-like cuts to constrain ggF contribution in VBF categories

VBF – Stage 1.



- VBF defined as electroweak $qq'H$ production
  - including usual VBF process and VH with hadronic V decays
- First split by p_T^{j1}
  - VBF topology cuts: $m_{jj} > 400\,\text{GeV}$ and $\Delta\eta_{jj} > 2.8$ (no other cuts)
  - $V(\to jj)H$ topology cuts: $60\,\text{GeV} < m_{jj} < 120\,\text{GeV}$
  - Rest: Everything not passing above (including events with < 2 jets)